AEROCAPTURE GUIDANCE PERFORMANCE FOR THE NEPTUNE ORBITER

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A performance evaluation of the Hybrid Predictor-corrector Aerocapture Scheme (HYPAS) guidance algorithm for aerocapture at Neptune is presented in this paper for a Mission to Neptune and the Neptune moon Triton[1]. This mission has several challenges not experienced in previous aerocapture guidance assessments. These challengers are a very high Neptune arrival speed, atmospheric exit into a high energy orbit about Neptune, and a very high ballistic coefficient that results in a low altitude acceleration capability when combined with the aeroshell L/D. The evaluation includes a definition of the entry corridor, a comparison to the theoretical optimum performance, and guidance responses to variations in atmospheric density, aerodynamic coefficients and flight path angle for various vehicle configurations (ballistic numbers). The benefits of utilizing angle-of-attack modulation in addition to bank angle modulation to improve flight performance is also discussed. The results show that despite large sensitivities in apoapsis targeting, the algorithm performs within the allocated ΔV budget for the Neptune mission using only bank angle modulation. The addition of angle-of-attack modulation with as little as ±5 degrees of amplitude significantly improves the accuracy in final orbit apoapsis. Although angle-of-attack modulation complicates the vehicle design its performance enhancement reduces aerocapture risk and reduces the propellant consumption needed to reach the high energy target orbit.

Nomenclature

c	=	Convective heat transfer coefficient
C_D	=	Aerodynamic drag coefficient
D	=	Drag acceleration
L	=	Lift acceleration
m	=	Vehicle mass
M	=	Planetary body mass
$\dot{q}_c$	=	Convective aerodynamic heating rate
r	=	Radial distance from center of planetary body
R_N	=	Aeroshell nose radius
A	=	Aerodynamic reference area
V	=	Relative velocity
ΔV	=	Change in velocity
γ	=	Inertial flight path angle
V_i	=	Inertial velocity
μ	=	Gravitational constant
ρ	=	Atmosphere density
σ	=	Bank angle

INTRODUCTION

The objective of the Neptune mission is to explore Neptune and one of its moons, Triton, in similar fashion to the Cassini-Huygens Mission. In addition to performing atmospheric observations and detailed gravity and magnetic field determination via two atmospheric entry probes and one orbiting vehicle, the final orbit of the vehicle is placed in a nominal 3,896 x 430,000 km orbit about the planet in order to allow observations of Triton, one of the moons of Neptune. Aerocapture is an efficient way to provide the energy dissipation from a high energy approach trajectory needed to enter into a low energy orbit about a planet during one pass through a planet's atmosphere. After the pass through the atmosphere, only a relatively small propulsive maneuver is required to place the spacecraft into the desired final orbit.

Aerocapture is considered enabling for this Neptune mission and provides significant reduction in mass or trip time for other planetary destinations[2,3]. This technique allows a spacecraft to capture into a desired orbit about a given body at significantly lower ΔV cost and thus provides an overall mass and cost savings to the mission. The Hybrid Predictor-corrector Aerocapture Scheme (HYPAS)[4] is a candidate for the aerocapture guidance algorithm. This algorithm has been analyzed extensively for aerocapture missions at Earth, Mars, and Titan, however aerocapture for this Neptune mission has challenges not encountered in previous aerocapture assessments. This paper addresses the challenges associated with the aerocapture mission at Neptune and defines the performance of the algorithm, including its sensitivity to perturbations in aerodynamics, atmospheric density, and the arrival state vector.

In the reference mission, the vehicle enters the atmosphere at an altitude of 1,000 km with an inertial velocity of 29.0 km/s. The vehicle uses a blunt body flat bottom ellipsled aeroshell[5], see Figure 1, with a ballistic number (m/C_DA) of 895 kg/m^2, and a lift-to-drag ratio (L/D) of 0.8. The aerocapture guidance algorithm targets the vehicle to a desirable atmospheric exit state vector that allows it to reach the targeted 430,000 km apoapsis.

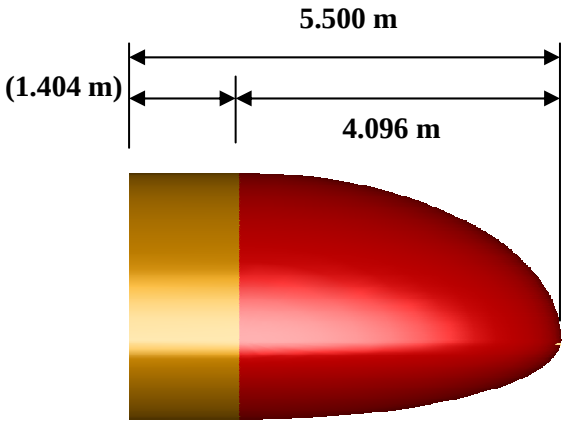


Figure 1. Aeroshell Geometry

NEPTUNE AEROCAPTURE CHALLENGES

The nature of the Neptune mission presents a set of new challenges to the guidance system. The low-thrust Solar Electric Power (SEP) trajectory brings the vehicle after a 10.25 year transit time to an entry velocity of 29.0 km/s; compared to typical missions to inner planets that present an entry velocity of approximately 11.0 km/s or lower, and earth return from planetary missions that may reach 13 km/s for a return from Mars. This high entry velocity associated with the Neptune mission causes the vehicle to experience large aerodynamic and thermodynamic loads that constrain the entry corridor.

The second challenge results from the high value of M/C_LA for the given vehicle design. Previous aerocapture missions used vehicles with M/C_LA of 400 kg/m^2 to 700 kg/m^2. Mass and packaging considerations for the Neptune mission result in a M/C_LA of more than 1,100 kg/m^2. M/C_LA is an inverse measure of control authority for altitude acceleration that is essential for efficient control of the drag acceleration profile. As can be seen in Figure 2, the altitude acceleration capability

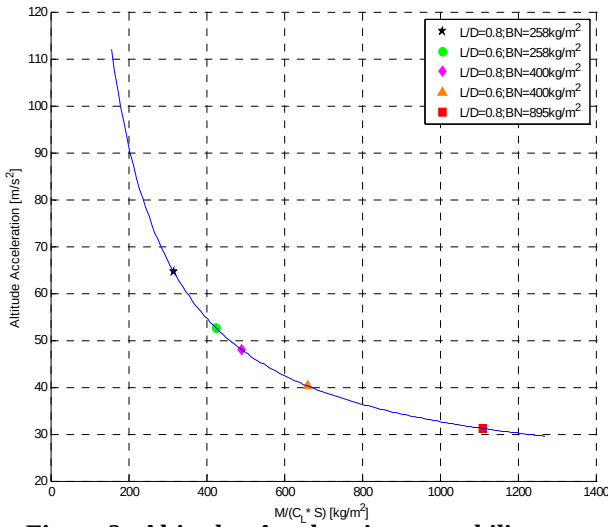


Figure 2. Altitude Acceleration capability vs. $M/(C_LA)$

decreases rapidly as the M/C_LA of the vehicle increases. The curve has been generated using the equation for normal to the velocity vector acceleration

$$\ddot{h} = \bar{q} \cdot \frac{C_L S}{m} \cdot \cos\sigma - \left[\frac{\mu}{R^2} - \frac{V_i^2}{R} \right] \cos\gamma, \tag{1}$$

where, μ= 6.8713e6 km^3/s^2, R = 24981705.48 m, V = 26872.0824 m/s and $\bar{q}_{max}$ = 14.753 kPa. As altitude acceleration capability decreases, it becomes more difficult for the vehicle to respond to random density perturbations in a timely manner.

The data was taken from the maximum dynamic pressure point in the nominal trajectory for a L/D of 0.8 and ballistic number of 258 kg/m^2 configuration. For simplification, the flight path angle, γ, and bank angle, σ, are assumed to be 0 deg. It can be seen that for a given point in a trajectory, the final configuration (L/D of 0.8 and ballistic number of 895 kg/m^2) provides only half the altitude acceleration capability as the counterpart with a lower ballistic number. This lack of control authority, will thus force the guidance system to seek a higher dynamic pressure, and thus force the vehicle into a steeper trajectory. While the steeper trajectory aids the guidance control, it also increases the thermodynamic loads on the vehicle, and is thus undesirable.

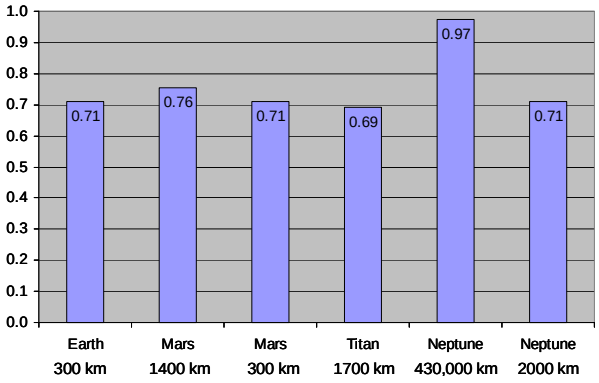
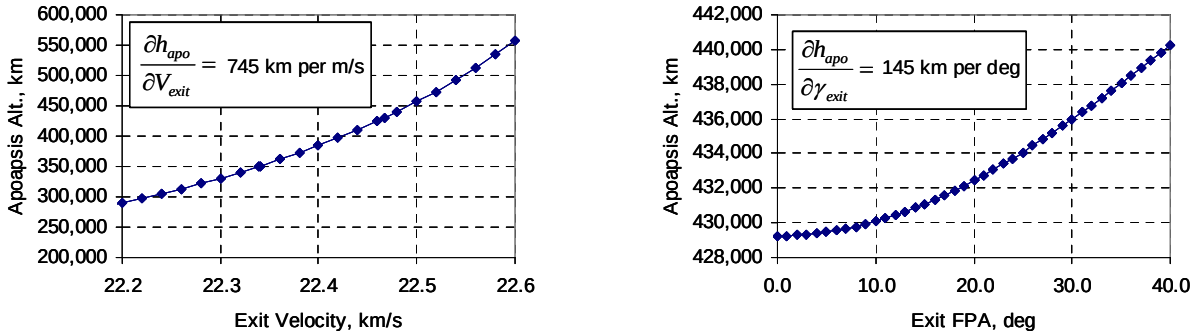
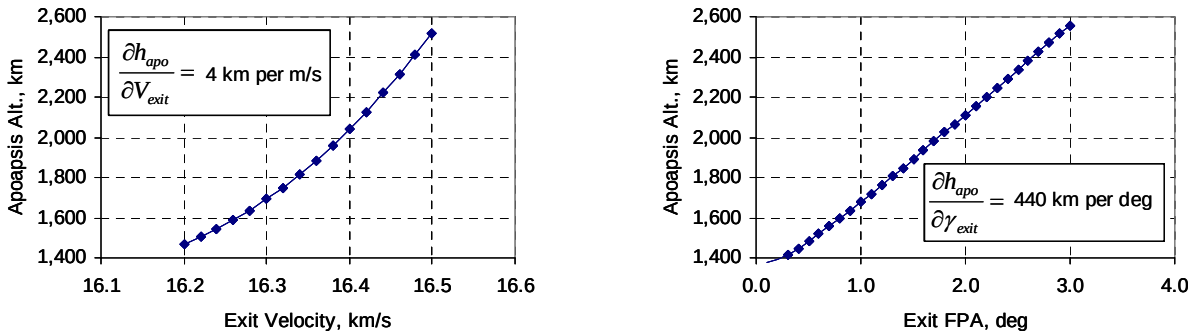


Figure 3. Ratio of Exit Velocity to Escape Velocity

Target Apoapsis Altitude: 430,000 km



Target Apoapsis Altitude: 2,000 km



Figures 4-7. Sensitivity to Atmospheric Exit Conditions

The third new challenge results from the high energy final target orbit of 3,896 x 430,000 km that requires an exit velocity near 22.5 km/s or about 97% of the Neptune escape speed. Figure 3 shows typical exit-to-escape velocity ratios for missions using aerocapture at other destinations with atmospheric exit at near orbital speed or about 71% of escape speed. The very high exit speed for this Neptune mission results in a large sensitivity of the post aerocapture orbit to the atmospheric exit conditions. This is illustrated in Figures 4-7, which show the effects of exit velocity error and exit flight path angle on apoapsis altitude as a function of the target apoapsis altitude for two different ranges of apoapsis altitudes that correspond to low and high energy planetary orbits. While the sensitivity to exit flight path angle is slightly larger for the 2,000 km target apoapsis altitude, a 1 m/s error in exit velocity yields a 745 km error in apoapsis altitude for the 430,000 km target versus a 4 km error for the 2000 km target, about two orders of magnitude larger.

DESCRIPTION OF TRAJECTORY SIMULATION

The Simulation and Optimization of Rocket Trajectories (SORT)[6] program was used to perform the numerical trajectory simulation. SORT is a multi-purpose computer program that uses three degrees-of-freedom to simulate the translation flight dynamics of an arbitrary aerospace vehicle about a given central body with phase plane logic to simulate the bank dynamics. The vehicle is assumed to be in an aerodynamically trimmed attitude. The simulation interface allows the user to easily adjust vehicle parameters, planet geometry, gravity model, and atmospheric model.

For the Neptune aerocapture trajectory simulation, the planet and gravity model used are based on a spherical body of radius 24,764 km with an inverse square gravity field with a gravitational parameter of 6.8713×10^6 km^3/s^2. The atmosphere model used for the trajectory simulation is the Neptune Global Reference Atmosphere Model (GRAM)[7]. Atmospheric density is computed as a function of altitude, and the engineering model allows a variation of the density profile between a minimum and maximum expected value that is includes the effects of latitude, seasonal, and diurnal effects. The parameter in the model that allows for this control (FMINMAX) can be varied continuously between -1.0 and +1.0, corresponding to the minimum and maximum expected mean density, respectively. A value of 0.0 produces a nominal density profile. The Neptune GRAM also has the capability to superimpose random density perturbations on the selected profile to model the relatively high frequency density gradients resulting from gravity waves. The simulation tool uses a Sutton-Graves[8] stagnation point convective heat rate equation,

$$\dot{q}_c = cV^3\sqrt{\frac{\rho}{R_N}}, \tag{2}$$

where $\dot{q}_c$ is the heating rate, V is the atmospheric relative velocity, ρ is the atmospheric density, R_N is the vehicle's nose radius, and c is the Sutton-Graves constant, which for Neptune is 6.96×10^{-9} kg$^{0.5}$/m.

The atmospheric entry conditions were taken from the proposed Neptune Triton Exploration Mission[1]. This mission results in an inertial entry velocity of 29 km/s at 1000 km altitude.

The Neptune entry vehicle uses bank angle to control the in-plane dynamics and bank reversal to control the trajectory inclination. This Neptune aerocapture assessment used the Hybrid Predictor-corrector Aerocapture Scheme (HYPAS) algorithm to develop the bank angle magnitude and bank reversal commands. This guidance algorithm was originally developed at the Johnson Space Center in mid 1980's as the guidance algorithm for the Aeroassist Flight Experiment (AFE). This analytically derived guidance algorithm uses drag based deceleration and altitude rate errors as feedback terms in the closed loop guidance operation. The algorithm has been extensively used in various different simulation studies of aerocapture into low energy planetary orbits, with a range of different initial state vectors, vehicle ballistic numbers, and lift-to-drag ratios, as well as multiple destinations, such as Earth, Mars, and Titan[9]. Guidance initialization constants and the feedback gains are used to control the profile shape and responsiveness to perturbations to achieve the desired dynamic pressure, heat rate, deceleration, and the total theoretical corridor capture.

The HYPAS guidance algorithm is divided into two flight phases, an equilibrium glide, and an exit phase. In the first phase, the algorithm generates bank angle commands to drive the vehicle towards a balance of lift, gravity, and centripetal forces, or equilibrium glide conditions to assure capture and control levels of loads. Once the vehicle has decelerated to a specified velocity, the exit phase is initiated. In this phase, the guidance computes a predicted velocity vector at atmospheric exit altitude, based on analytically derived equations. The bank angle is commanded to adjust the exit state so that the vehicle can achieve the desired target apoapsis. The robustness of the algorithm

stems from the ability to individually tune the initialization parameters for both phases, allowing for a controlled and stable capture, and maximum performance during exit.

PERFORMANCE FOR NEPTUNE AEROCAPTURE

The first step in the performance analysis of the guidance system involves determination of the theoretical entry flight path angle corridor. This corridor is used to define the limits on the arrival flight path angle as well as to define the nominal, or target, entry flight path angle. An optimum aerocapture flight profile is developed for this entry corridor. Development of this profile is a multi-step process of defining the aerocapture guidance initialization parameters and testing the effect on variations to entry flight path angle, aerodynamic coefficients, and atmospheric density throughout the entry corridor. The final step in the analysis is a Monte Carlo simulation; to assess the overall performance of the guidance algorithm under expected random flight conditions.

THEORETICAL ENTRY CORRIDOR

Defining the theoretical entry corridor allows for a definition of the desired nominal entry flight path angle as well as the limitations on navigation errors of delivery. The steep side of the corridor is defined as the steepest entry flight path angle which allows the vehicle to just reach the target apoapsis while flying lift vector up over the entire duration of the flight. The shallow side of the corridor is defined as the shallowest entry flight path angle which allows the vehicle to just reach the target apoapsis while flying lift vector down over the entire duration of the flight.

For this assessment, the theoretical entry flight path angle corridor was determined by using the Neptune GRAM with the nominal, minimum, and maximum atmospheric density profiles to account for the uncertainty in the density profile (see Table 1). A combined corridor was developed that includes the effects of atmospheric density variations and this results in an entry corridor of 1.78 deg. This corridor is sufficiently large enough to accommodate the expected delivery errors. The nominal entry flight path angle was chosen to be –12.77 deg, the middle of this combined theoretical corridor.

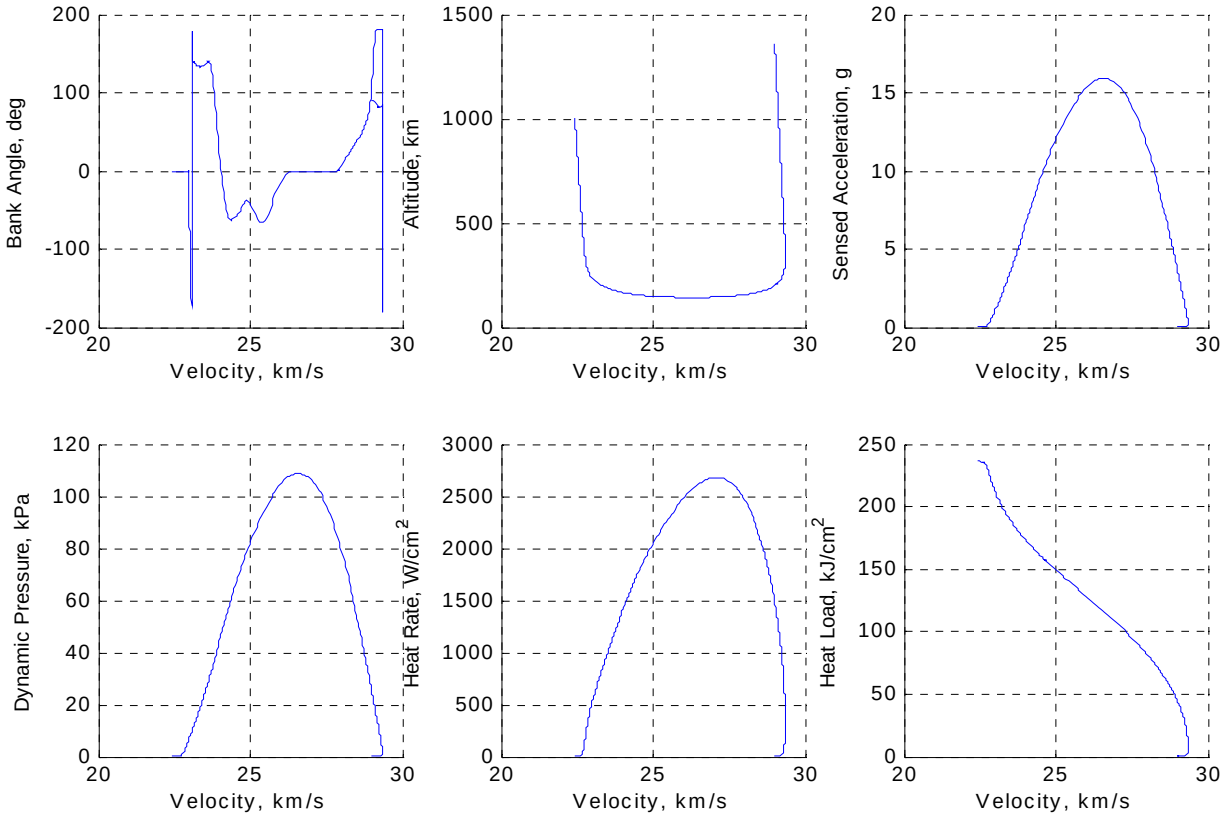
Atmosphere	Steep Side (deg)	Shallow Side (deg)	Width (deg)	Middle (deg)
Nominal	-13.81	-11.49	2.32	-12.65
Minimum	-13.96	-11.88	2.09	-12.92
Maximum	-13.66	-11.08	2.58	-12.37
Combined	-13.66	-11.88	1.78	-12.77

Table 1. Theoretical Entry Flight Path Angle

AEROCAPTURE FLIGHT PROFILE

Once the theoretical entry corridor is defined, an optimum performance for the guidance algorithm can be determined. By having the vehicle fly full lift up as it enters the atmosphere and then command the vehicle to bank to a full lift down attitude at the correct instant in order to achieve the precise target apoapsis altitude, a maximum periapsis altitude is achieved. Maximizing the periapsis altitude thus minimizes the post-aerocapture ΔV required to place the vehicle into the desired target orbit. For each given entry flight path angle, an exact point to switch from lift up to lift down can be identified. The closer the vehicle is to the shallow side of the corridor, the closer the switch time is to the entry condition. For an entry at the opposite (steep) side of the corridor, no switch is performed, allowing the vehicle to fly full lift up through the entire flight. The theoretical optimum performance is not a practical method of guiding the vehicle through the flight, however it provides valuable information on how the actual flight algorithm compares to a theoretical optimum performance.

The nominal guidance performance was achieved by adjusting the algorithm initialization parameters for the reference mission. Trajectory simulations with HYPAS show that the algorithm performs well under the given conditions. Important to note however is that for the nominal entry flight path angle (center of corridor) there are periods during the flight in which the bank angle is saturated, full lift up or down. This is attributed to the high ballistic number and high M/C_LA of the vehicle. The lack of control authority of the vehicle drives the guidance to initially fly a very steep profile in order to achieve a high dynamic pressure and thus attain the desired control. Then the vehicle must fly full lift up to maintain an equilibrium glide condition and initiate the exit. When the algorithm was tuned in such a manner to minimize this saturation period, the large random density perturbations overwhelmed the system and causes larger then desired error in apoapsis targeting because the system would not respond aggressively enough. The nominal profile can be seen in Figures 8-13.



Figures 8-13. Nominal Guidance Profile

AEROCAPTURE GUIDANCE PERFORMANCE

The aerocapture guidance performance was evaluated throughout the entry corridor for nominal and dispersed atmospheres and aerodynamic characteristics. This performance is illustrated in Figure 14 for nominal flight conditions and in figures 15 and 16 for dispersed atmospheres and aerodynamic characteristics. Figure 14 shows apoapsis altitude throughout the entry corridor and shows that the guidance performs well and captures 93% of the corridor, as defined by the 390,000 and 490,000 km apoapsis altitude band. It is important to note that 100% of the cases remained captured into orbit. The results were generated using the nominal mean atmospheric profile (FMINMAX of 0.0), and no random density perturbations were used.

The sensitivity of the HYPAS algorithm to uncertainties in atmospheric conditions and aerodynamic coefficients is illustrated in Figures 15 and 16. The algorithm was subjected to the limits of the expected atmospheric model, the minimum and maximum profile. Figure 15 shows that the guidance handles the maximum profile in a good fashion, only losing slight corridor width on the steep side. Conversely under the minimum atmospheric profile the system the guidance is unable to accommodate the shallower angles. Since the atmosphere has a lower density, it effectively shifts the corridor towards steeper entry angles. Note that in this figure, the shallowest angle, corresponding to –11.9 deg, results in an atmospheric skip, or a negative apoapsis altitude, due to the hyperbolic nature of the orbit.

To simulate possible aerodynamic errors, a ±10 percent variation in lift and drag coefficient was implemented and individually evaluated to assess the extreme response of the

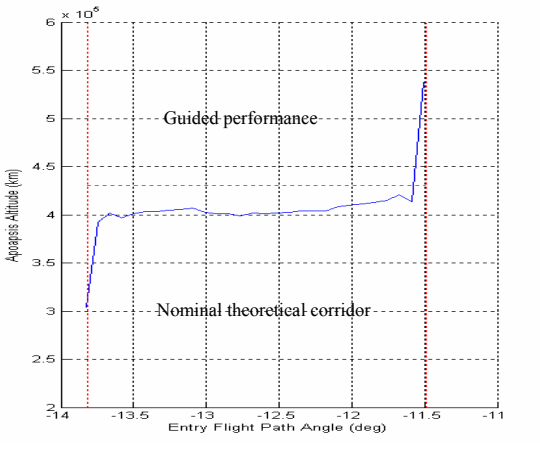


Figure 14. Nominal Guidance Performance

guidance algorithm. The results of this assessment can be seen in Figure 16. Here it can be seen that there is a slight loss of the corridor capture in the +10 percent in C_D and –10 percent in C_L cases, but all cases remain in orbit. The effects are limited to the ability of targeting the desired apoapsis altitude.

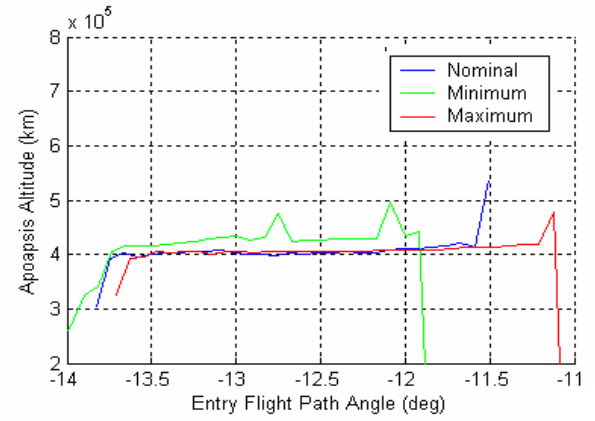


Figure 15. Atmospheric Sensitivity

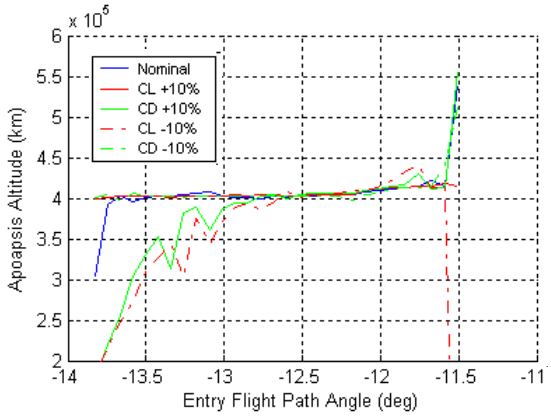


Figure 16. Aerodynamic Sensitivity

ANGLE OF ATTACK MODULATION

Angle-of-attack modulation is used by the Space Shuttle Orbiter entry guidance[10] to improve the performance compared to control with only bank angle modulation. This results in a rapid response to trajectory perturbations by directly changing the area exposed to the flow and thus the drag. The original derivation of HYPAS includes only bank angle modulation, which by moving the lift vector affects the altitude rate of the vehicle and controls the density environment of flight. This then can be translated to drag deceleration modulation. The new set of difficulties encountered in the Neptune mission, lead to a desire for improved control in order to improve the final orbit apoapsis targeting.

The HYPAS algorithm was modified, as shown in equations (3) through (6) to incorporate angle-of attack modulation. The approach taken here is derived from that used for angle of attack modulation on the Space Shuttle. The $\Delta\alpha$ formulation is used to command a change in angle-of-attack relative to the current angle-of-attack. The variation in angle-of-attack from the nominal profile is limited to a specific value, here tested at 3, 5, and 10 deg to limit the effects on aerodynamic heating.

$$\alpha_{cmd} = \alpha + \Delta\alpha \tag{3}$$

$$\Delta\alpha = \frac{C_D\left(D_{ref} - D\right)}{\bar{q}G_{\Delta\alpha}} \tag{4}$$

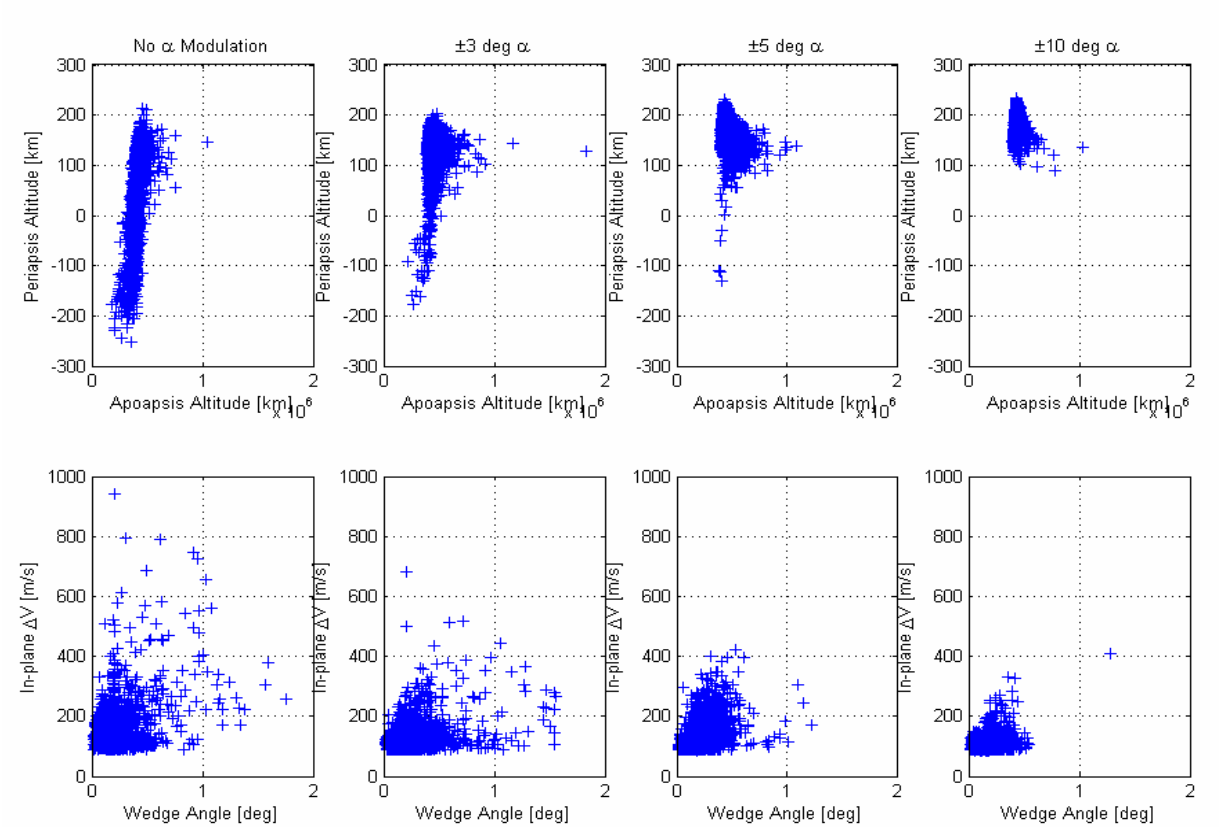
The HYPAS equation then for bank angle is modified to drive the angle-of-attack back to a nominal profile. The original and new bank command equation can be seen in equation (5) and (6),

$$\left(\frac{L}{D}\right)\cos\phi_{cmd} = \frac{C_L}{C_D}\left[\cos\phi_{eq.gl.} - G_h\left(\frac{\dot{h}-\dot{h}_{ref}}{\bar{q}}\right) + G_D\left(\frac{D-D_{ref}}{\bar{q}}\right)\right] \tag{5}$$

$$\left(\frac{L}{D}\right)\cos\phi_{cmd} = \frac{C_L}{C_D}\left[\cos\phi_{eq.gl.} - G_h\left(\frac{\dot{h}-\dot{h}_{ref}}{\bar{q}}\right) + G_D\left(\frac{D-D_{ref}}{\bar{q}}\right) + G_\alpha\left(\alpha_{nom} - \alpha_{cmd}\right)\right] \tag{6}$$

where ϕ_{cmd} is the commanded bank angle, G_h, G_D, and G_α are the feedback gains for altitude rate, drag deceleration, and angle of attack respectively.

Various ranges of angle of attack modulation limit were initially investigated as an option to improving the performance. In the Monte Carlo performance analysis (Figures 17-24), it can be seen that an angle modulation of ±5 degree can provide significant improvements in the precision of the algorithm. The in-plane ΔV to maneuver the vehicle into the target orbit is also shown. This analysis was conducted as a preliminary assessment. The actual implementation method for angle of attack modulation, such as body flaps, jets, or CG shift, was not investigated, and should be included in further analysis. The addition of angle attack modulation, though increasing the complexity of the system has potential propellant mass savings. Using the 3σ ΔV value for no angle of attack modulation of 378.7 m/s, an initial vehicle mass of 2200 kg, and assuming a typical bipropellant Isp of 320 sec, yields a propellant mass of approximately 250 kg. In contrast, using the 3σ ΔV value for ±10 deg angle of attack modulation of 176.5 m/s, yields a propellant mass of approximately 120 kg, more then 50% savings in mass.



Figures 17-24. Angle of Attack Modulation

SUMMARY AND CONCLUSIONS

The HYPAS guidance algorithm performance for a Neptune aerocapture mission has been investigated. The investigation included development of a nominal guided flight profile, determination of the amount of the theoretical entry corridor captured with the algorithm, and algorithm performance under perturbations in aerodynamics, atmosphere density, and entry state vector using Monte Carlo simulations. The results show that the algorithm performance meets the given propulsive ΔV allotment and satisfies the reference mission requirements. Detailed aerocapture orbit insertion performance for the Neptune Triton Exploration mission can be found in Reference 11.

It was found that mission parameter values unique to the Neptune aerocapture mission investigated here, specifically, the combination of high vehicle ballistic coefficient, high entry velocity, and high energy target orbit, posed difficulties that have not been experienced in previous assessments of aerocapture guidance algorithm performance. The net effect of the extreme values of these parameters is a decrease in the accuracy of achieving the

target apoapsis with aerocapture using bank angle control only, thus resulting in a larger than expected post-aerocapture propulsive maneuver. Angle of attack modulation has been incorporated into the HYPAS algorithm to address this issue. Monte Carlo trajectory simulations show that with angle of attack modulation, the accuracy for the given Neptune mission is significantly improved, resulting in a decrease in the propulsive ΔV requirements and reduction in risk of the aerocapture maneuver.

The difficulties encountered in the guidance design for the stressful conditions of the Neptune mission highlights the need to further investigate future changes to the algorithm for this application. This includes an improved reference drag profile to more closely match the flight profile and further investigation of angle of attack control. Further iterations of tuning can also yield an improved bank angle profile, with less control saturation.

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